QCD predictions of c and b production at RHIC

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Abstract. We make up-to-date QCD predictions for heavy flavor production in $\sqrt{S} = 200$ GeV pp collisions at RHIC. We also calculate the electron spectrum from heavy flavor decays to directly compare to the data. A rigorous benchmark, including the theoretical uncertainties, is established against which nuclear collision data can be compared to obtain evidence for dense matter effects.

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In the spirit of continuing to validate the perturbative QCD framework for heavy flavor production, discussed in Ref. [1], which works rather well, it is important to continue to confront it with new data such as that obtained at RHIC by PHENIX [2] and STAR [3, 4]. Comparison of the pp and d+Au data at $\sqrt{S_{NN}} = 200$ GeV with benchmark calculations will aid in the interpretation of heavy flavor production in nucleus-nucleus collisions.

We calculate the transverse momentum (p_T) distributions of charm and bottom quarks, the charm and bottom hadron distributions resulting from fragmentation and, finally, the electrons produced in semileptonic decays of the hadrons [1]. Theoretical uncertainties are also estimated. Our final prediction is thus an uncertainty band which has a reasonably large probability of containing the 'true' theoretical prediction.

The theoretical prediction of the electron spectrum includes three main components: the p_T and rapidity distributions of the heavy quark, Q, in pp collisions at $\sqrt{S} = 200$ GeV, calculated in perturbative QCD; fragmentation of the heavy quarks into heavy hadrons, H_Q, described by phenomenological input extracted from e^+e^- data; and the decay of H_Q into electrons according to spectra available from other measurements. This cross section is schematically written as

$$\frac{Ed^3\sigma(e)}{dp^3} = \frac{E_Q d^3\sigma(Q)}{dp_Q^3} \otimes D(Q \to H_Q) \otimes f(H_Q \to e) \tag{1}$$

where the symbol $\otimes$ denotes a generic convolution. The electron decay spectrum, $f(H_Q \to e)$, accounts for the branching ratios.

The distribution $Ed^3\sigma(Q)/dp_Q^3$ is evaluated at Fixed-Order plus Next-to-Leading-Log (FONLL) level, implemented in Ref. [5]. In addition to including the full fixed-order NLO result [6, 7], the FONLL calculation also resums [8] large perturbative terms proportional to $\alpha_s^n \log^k(p_T/m)$ to all orders with next-to-leading logarithmic (NLL) accuracy (i.e. $k = n, n-1$) where m is the heavy quark mass. The perturbative parameters are m and the value of the strong coupling, α_s. We take $m_c = 1.5$ GeV and $m_b = 4.75$ GeV as central values and vary the masses in the range $1.3 < m_c < 1.7$ GeV for charm and

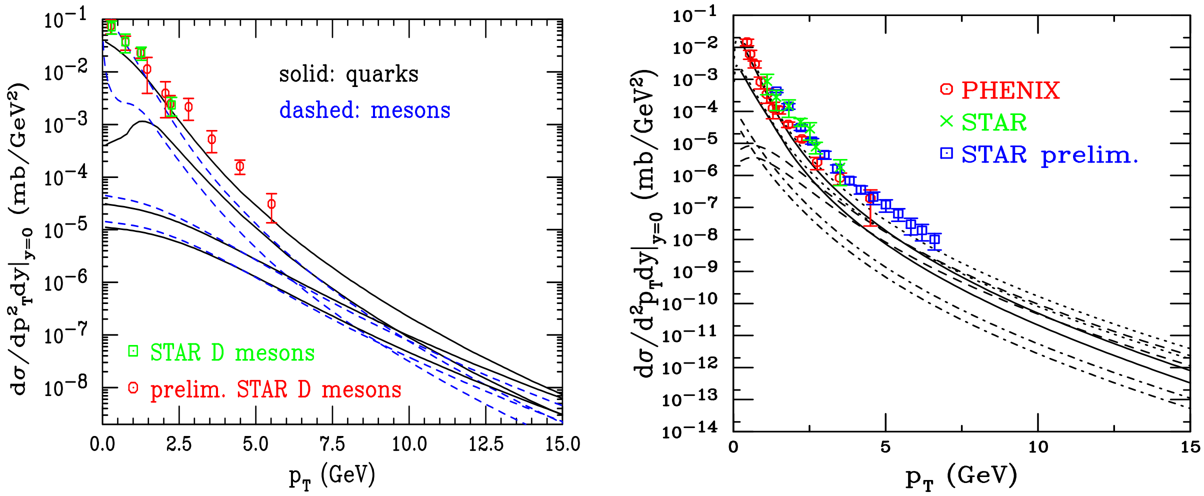

FIGURE 1. Left-hand side: The theoretical uncertainty bands for heavy quark (solid) and meson (dashed) p_T distributions in pp collisions at $\sqrt{S} = 200$ GeV, using BR($Q \to H$) = 1. The upper bands are for charm, the lower for bottom. The final [3] and preliminary [4] STAR d+Au data (scaled to pp using $N_{\rm bin}$ = 7.5) are also shown. Right-hand side: The theoretical uncertainty bands for $D \to e$ (solid), $B \to e$ (dashed) and $B \to D \to e$ (dot-dashed) and the sum (dotted) as a function of p_T in $\sqrt{S} = 200$ GeV pp collisions. The results are compared to the PHENIX [2] and STAR (final [3] and preliminary [4]) data.

$4.5 < m_b < 5$ GeV for bottom to estimate the mass uncertainties. The five-flavor QCD scale is the CTEQ6M value, $\Lambda^{(5)} = 0.226$ GeV. The perturbative calculation also depends on the factorization (μ_F) and renormalization (μ_R) scales. The scale sensitivity is a measure of the perturbative uncertainty. We take $\mu_{R,F}^2 = \mu_0^2 = p_T^2 + m^2$ as the central value and vary the two scales independently within a 'fiducial' region defined by $\mu_{R,F} = \xi_{R,F}\mu_0$ with $0.5 \leq \xi_{R,F} \leq 2$ and $0.5 \leq \xi_R/\xi_F \leq 2$ so that $\{(\xi_R, \xi_F)\}$ = {(1,1), (2,2), (0.5,0.5), (1,0.5), (2,1), (0.5,1), (1,2)}. The mass and scale uncertainties are added in quadrature and the resulting envelope defines the uncertainty. The fragmentation functions, $D(c \to D)$ and $D(b \to B)$, where D and B indicate a generic admixture of charm and bottom hadrons, are consistently extracted from e^+e^- data in the context of FONLL [9].

The measured spectra for primary $B \to e$ and $D \to e$ decays are assumed to be equal for all bottom and charm hadrons, respectively. The contribution from secondary B decays, $B \to D \to e$, gives a negligible contribution to the total. The decay spectra are normalized using the branching ratios for bottom and charm hadron mixtures [10]: $\mathrm{BR}(B \to e) = 10.86 \pm 0.35\%$, $\mathrm{BR}(D \to e) = 10.3 \pm 1.2\%$, and $\mathrm{BR}(B \to D \to e) = 9.6 \pm 0.6\%$.

The left-hand side of Fig. 1 shows the theoretical uncertainty bands for heavy quarks and mesons, obtained by summing the mass and scale uncertainties in quadrature. The charm band (upper curves) is broader at low p_T due to the large value of α_s and the behavior of the CTEQ6M parton densities at low scales as well as the increased sensitivity of the cross section to the charm quark mass. The rather hard fragmentation function causes the D meson and c quark bands to separate only at $p_T > 9$ GeV. The harder $b \to B$ fragmentation function causes the two bands to partially overlap until $p_T \simeq 20$ GeV.

The right-hand side of Fig 1 shows the individual uncertainty bands for the $D \to e$, $B \to e$ and $B \to D \to e$ decays to electrons as well as the sum of all contributions. The upper and lower limits of the band are obtained by summing the upper and lower limits for each component. The secondary $B \to D \to e$ spectrum is always negligible with respect to the total yield. While, for the central parameter sets, the $B \to e$ decays begin to dominate the $D \to e$ decays at $p_T \simeq 4$ GeV, a comparison of the bands shows that the crossover may occur over a rather broad range of electron p_T. The relative c and b decay contributions may play an important part in understanding the electron R_{AA} in nucleus-nucleus collisions [11, 12] which seems to suggest strong energy loss effects on heavy flavors [13, 14].

We have presented theoretical uncertainty bands for heavy quarks, mesons and their electron decay products as a function of p_T in $\sqrt{S} = 200$ GeV pp collisions at RHIC. These results should not be multiplied by any K factor. Rather, agreement within the uncertainties of the data would support the applicability of perturbative QCD to heavy quark production at RHIC. Significant disagreement would suggest that this evaluation needs to be complemented by further ingredients.

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